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14. ABSTRACT

Optically-trapped, strongly-interacting Fermi gases are models for exotic strongly-interacting systems in nature. For this reason, tabletop experiments with strongly-interacting atomic Fermi gases can provide measurements that are relevant to all strongly-interacting Fermi systems, thus impacting theories in

15. SUBJECT TERMS

Fermions, Atom traps, CO2 Laser

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## Report Title

Strongly-Interacting Fermi Gases in Reduced Dimensions

## ABSTRACT

Optically-trapped, strongly-interacting Fermi gases are models for exotic strongly-interacting systems in nature. For this reason, tabletop experiments with strongly-interacting atomic Fermi gases can provide measurements that are relevant to all strongly-interacting Fermi systems, thus impacting theories in intellectual disciplines outside atomic physics, including materials science and condensed matter physics (superconductivity), nuclear physics (nuclear matter), high-energy physics (effective theories of the strong interactions), astrophysics (compact stellar objects), the physics of quark-gluon plasmas (elliptic flow), and most recently, string-theory (minimum viscosity hydrodynamics).

Recent experiments have been carried out in a three dimensional geometry, where the adiabatic local density approximation is valid. The purpose of this program is to explore strongly-interacting Fermi gases in a two-dimensional pancake geometry, where the simplest approximations break down.

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## List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

### (a) Papers published in peer-reviewed journals (N/A for none)

1) J. E. Thomas, J. Kinast and A. Turlapov, ``Virial theorem and universality in a unitary Fermi gas," Phys. Rev. Lett. vol. 95, 120402 (2005).

2) J. Kinast, A. Turlapov, and J. E. Thomas, ``Optically trapped Fermi gases model strong interactions in nature," Opt. Phot. News, vol 16, 21 (December, 2005).

3) J. E. Thomas, ``Atom cooling: Ultracold Fermi gas on a chip," Nature Physics vol. 2, 377-378 (2006).

4) J. E. Thomas, J. Kinast, and A. Turlapov, ``Optically-trapped Fermi gases," Habitation vol. 10, 242 (2006).

5) L. Luo, B. Clancy, J. Joseph, J. Kinast, A. Turlapov, and J. E. Thomas, ``Evaporative cooling of a unitary Fermi mixtures in optical traps," New J. Phys. vol. 8, 213 (2006).

6) L. Luo, B. Clancy, J. Joseph, J. Kinast, and J. E. Thomas, ``Measurement of the entropy and critical temperature of a strongly interacting Fermi gas," Phys. Rev. Lett. vol. 98, 080402 (2007).

7) J. Joseph, B. Clancy, L. Luo, J. Kinast, A. Turlapov, and J. E. Thomas, ``Measurement of sound velocity in a Fermi gas near a Feshbach resonance," Phys. Rev. Lett. vol. 98, 170401 (2007).

8) B. Clancy, L. Luo, and J. E. Thomas, ``Observation of nearly perfect irrotational flow in normal and superfluid strongly interacting Fermi gases," Phys. Rev. Lett. vol. 99, 140401 (2007).

9) A. Turlapov, J. Kinast, B. Clancy, L. Luo, J. Joseph, and J. E. Thomas, ``Is a gas of strongly interacting atomic fermions a nearly perfect fluid?," JLTP vol. 150, 567 (2008).

10) X. Du, L. Luo, B. Clancy, and J. E. Thomas, ``Observation of anomalous spin segregation in a trapped Fermi gas," Phys. Rev. Lett., vol. 101, 150401 (2008).

**Number of Papers published in peer-reviewed journals:** 10.00

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## (b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

1) J. E. Thomas, J. Kinast, and A. Turlapov, ``Thermodynamics and mechanical properties of a strongly-interacting Fermi gas," Proceedings of the 17th International Conference on Laser Spectroscopy, Aviemore, Scotland (June 19-24, 2005), E. A. Hinds, A. Ferguson and E. Riis editors, p.223-238 (World Scientific London 2005).

2) J. E. Thomas, J. Kinast, and A. Turlapov, ``Universal thermodynamics of a strongly interacting Fermi gas," in Low temperature Physics: 24$^{th}$ International Conference on Low Temperature Physics; edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirshfeld, and A. M. Goldman, AIP Conference Proceedings, vol. 850, 69-76 (2006).

3) J. E. Thomas, J. Joseph, B. Clancy, L. Luo, J. Kinast, and A. Turlapov, ``Optical trapping and fundamental studies of atomic Fermi gases," Proceedings of the SPIE, vol. 6326, 632602 (2006).

**Number of Papers published in non peer-reviewed journals:** 3.00

## (c) Presentations

1) J. E. Thomas, ``Thermodynamical and mechanical properties of a strongly-interacting Fermi gas," 17th International Conference on Laser Spectroscopy (Aviemore, Scotland, June 19-24, 2005).

2) J. E. Thomas, ``Dynamics and thermodynamics of a strongly-interacting Fermi gas," European Science Foundation Exploratory Workshop: New phenomena in Superfluidity and Superconductivity, (Camerino, Italy, July 4-5, 2005), talk given by A. Turlapov.

3) J. E. Thomas, J. Kinast, and A. Turlapov, ``Universal thermodynamics of a strongly-interacting Fermi gas," 24th International Conference on Low Temperature Physics, Orlando, Florida (August 10-17, 2005), Plenary Talk.

4) J. E. Thomas, ``Thermodynamics and superfluidity of a strongly-interacting Fermi gas," ESF Research Conference on Bose-Einstein Condensation," (San Feliu de Guixols, Spain, September 10-15, 2005).

5) J. E. Thomas, ``Atomic Fermi gases with strong interactions: Superconductors, neutron stars and quark-gluon plasmas on a desktop," Seminar on Modern Optics and Spectroscopy, M. I. T., (Cambridge, MA, November 8, 2005).

6) J. E. Thomas, ``Optically-trapped Fermi gases," Habitation 2006 (February 5-8, 2006, Orlando, FL).

7) J. E. Thomas, ``Optically-trapped atomic Fermi gases," (April 6, 2006, Los Alamos National Laboratory).

8) J. E. Thomas, ``Collective modes and sound velocity in a strongly interacting Fermi gas," Strong correlations in Fermi systems (June 13-16, 2006, Copenhagen, Denmark).

9) J. E. Thomas, ``Testing the Equation of State of a Strongly Interacting Fermi Gas," International Symposium on Quantum Fluids and Solids, (August 1-6, 2006, Kyoto, Japan).

10) J. E. Thomas, ``Optical Trapping and Cooling of Fermi Gases," Shanghai Institute for Optics and Fine Mechanics (August 7, 2006, Shanghai, China).

11) J. E. Thomas, J. Joseph, B. Clancy, L. Luo, J. Kinast, and A. Turlapov, `` Optical trapping and fundamental studies of atomic Fermi gases," Proceedings, Optics and Photonics 2006 (August 13-17, San Diego, 2006).

12) J. E. Thomas,``Quantum dynamics of a strongly interacting Fermi gas," 2006 DOE Atomic, Molecular and Optical Sciences Research Meeting (Warrenton, VA, September 10-13, 2006).

13) J. E. Thomas, ``Optically-trapped, strongly interacting Fermi gases," The College of William and Mary (Williamsburg, VA, September 22, 2006).

14) J. E. Thomas, ``Optical trapping of atomic Fermi gases," Fitzpatrick Center, Duke University (November 7, 2006, Durham, NC).

15) J. E. Thomas, ``Optically-trapped, strongly interacting Fermi gases," University of Maryland (November 14, 2006, Baltimore, Md).

16) ``Quantum viscosity of a strongly-interacting Fermi gas," Workshop ``The interface of quark-gluon plasma physics and cold-atom physics," (Trento, Italy, March 19-23, 2007). Talk given by Andrey Turlapov.

17) J. E. Thomas, ``Thermodynamic measurements in a strongly interacting Fermi gas," 38th Annual Meeting DAMOP (June 5-9. 2007, Calgary, Alberta, Canada).

18) ``Why does a gas of strongly interacting fermions behave as a nearly perfect fluid?", International symposium on quantum fluids and solids (August 1-6, 2007, Kazan, Russia). Talk given by Andrey Turlapov.

19) J. E. Thomas, ``Strongly interacting Fermi gases as nearly perfect fluids," presented at Bose-Einstein Condensation 2007: Frontiers in Quantum Gases," (San Feliu de Guixoles, Spain, September 15-20, 2007).

20) J. E. Thomas, ``Is a strongly interacting Fermi gas a perfect fluid?," (University of Tennessee, Knoxville, October 1, 2007).

21) J. E. Thomas, ``Is a strongly interacting Fermi gas a perfect fluid?," (University of Toronto, Toronto, October 15, 2007.)

22) J. E. Thomas, ``Is a strongly interacting Fermi gas a perfect fluid?," (York University, Toronto, October 16, 2007).

23) J. E. Thomas, "Is a strongly interacting Fermi gas a perfect fluid?," (Yale University, New Haven, Conn., April 4, 2008).

24) J. E. Thomas, "Corraling Ultracold Atomic Gases in Bowls made of Laser Light," (UNC Wilmington, April 17, 2008).

25) J. E. Thomas, "Is a strongly interacting Fermi gas a perfect fluid?," (UNC Wilmington, April 18, 2008).

26) J. E. Thomas, "Fermi gases with tunable interactions," (International Conference on Atomic Physics, Storrs, Conn. July 27-Aug 1, 2008).

27) J. E. Thomas, "Searching for perfect fluidity in a strongly interacting Fermi gas," SFB-CoMat"-Joint Seminar, University of Ulm, Stuttart, and Tubingen (University of Tubingen, Germany, September 21, 2008).

28) J. E. Thomas, "Measurement of entropy and quantum viscosity in a strongly interacting atomic Fermi gas," at Quark-gluon plasma meets cold atoms," (Darmstadt, Germany, September 24-26, 2008), plenary talk.

29) J. E. Thomas, "Searching for perfect fluidity in an atomic Fermi gas," 7th Annual Meeting of the Fitzpatrick Institute for Photonics (FIP), (Duke University, October 13-14, 2008), plenary talk.

30) J. E. Thomas, "Resonantly interacting Fermi gases," Frontiers of Degenerate Quantum Gases, International Conference at Tsinghua Science Park (Beijing, China, October 20-24, 2008).

31) J. E. Thomas, "Searching for perfect fluidity in a Fermi gas," (Stonybrook, November 11, 2008).

32) J. E. Thomas, "Searching for perfect fluidity in a Fermi gas," (NCSU, November 17, 2008).

33) J. E. Thomas, "Interacting Fermi gases in optical traps," DARPA/ARO/AFOSR Joint Meeting, (Las Vegas, December 15-18, 2008).

**Number of Presentations:** 33.00

## Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):** 0

## Peer-Reviewed Conference Proceeding publications (other than abstracts):

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):** 0

## (d) Manuscripts

**Number of Manuscripts:** 0.00

**Number of Inventions:**

### Graduate Students

| NAME | PERCENT_SUPPORTED |
|---|---|
| Joseph Kinast | 0.50 |
| Le Luo | 0.50 |
| Bason Clancy | 0.50 |
| James Joseph | 0.10 |
| **FTE Equivalent:** | **1.60** |
| **Total Number:** | **4** |

### Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| Andrey Turlapov | 0.50 |
| Xu Du | 1.00 |
| **FTE Equivalent:** | **1.50** |
| **Total Number:** | **2** |

### Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
|---|---|---|
| John E. Thomas | 0.10 | No |
| **FTE Equivalent:** | **0.10** | |
| **Total Number:** | **1** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED |
|---|---|
| Ingrid Kaldre | 0.00 |
| Morgan Brown | |
| Eric Tong | 0.00 |
| David Weisberg | 0.00 |
| **FTE Equivalent:** | **0.00** |
| **Total Number:** | **4** |

## Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

| | |
|---|---|
| The number of undergraduates funded by this agreement who graduated during this period: ...... | 4.00 |
| The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... | 4.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... | 4.00 |
| Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): ...... | 2.00 |
| Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: ...... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ...... | 0.00 |

## Names of Personnel receiving masters degrees

| NAME | |
|---|---|
| **Total Number:** | |

## Names of personnel receiving PHDs

| NAME | |
|---|---|
| Joseph Kinast | |
| Le Luo | |
| Bason Clancy | |
| **Total Number:** | 3 |

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Sub Contractors (DD882)

# Inventions (DD882)

FINAL REPORT

1. PERIOD COVERED BY REPORT: 15 May 2005 - 14 November 2008

2. TITLE OF PROPOSAL: Strongly-Interacting Fermi Gases in Reduced Dimensions

3. CONTRACT OR GRANT NUMBER: W911NF-05-1-0273

4. NAME OF INSTITUTION: Duke University

5. AUTHORS OF REPORT: J. E. Thomas

6. LIST MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORT PERIOD, INCLUDING JOURNAL REFERENCES:

1) J. E. Thomas, J. Kinast and A. Turlapov, "Virial theorem and universality in a unitary Fermi gas," Phys. Rev. Lett. **95**, 120402 (2005).
2) J. Kinast, A. Turlapov, and J. E. Thomas, "Optically trapped Fermi gases model strong interactions in nature," Opt. Phot. News, **16**, 21 (December, 2005).
3) J. E. Thomas, J. Kinast, and A. Turlapov, "Thermodynamics and mechanical properties of a strongly-interacting Fermi gas," Proceedings of the 17th International Conference on Laser Spectroscopy, Aviemore, Scotland (June 19-24, 2005), E. A. Hinds, A. Ferguson and E. Riis editors, p.223-238 (World Scientific London 2005).
4) J. E. Thomas, "Atom cooling: Ultracold Fermi gas on a chip," Nature Physics **2**, 377-378 (2006).
5) J. E. Thomas, J. Kinast, and A. Turlapov, "Optically-trapped Fermi gases," Habitation **10**, 242 (2006).
6) J. E. Thomas, J. Kinast, and A. Turlapov, "Universal thermodynamics of a strongly interacting Fermi gas," in Low temperature Physics: $24^{th}$ International Conference on Low Temperature Physics; edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirshfeld, and A. M. Goldman, AIP Conference Proceedings, **850**, 69-76 (2006).
7) J. E. Thomas, J. Joseph, B. Clancy, L. Luo, J. Kinast, and A. Turlapov, "Optical trapping and fundamental studies of atomic Fermi gases," Proceedings of the SPIE, **6326**, 632602 (2006).
8) L. Luo, B. Clancy, J. Joseph, J. Kinast, A. Turlapov, and J. E. Thomas, "Evaporative cooling of a unitary Fermi mixtures in optical traps," New J. Phys. **8**, 213 (2006).
9) L. Luo, B. Clancy, J. Joseph, J. Kinast, and J. E. Thomas, "Measurement of the

entropy and critical temperature of a strongly interacting Fermi gas," Phys. Rev. Lett. **98**, 080402 (2007).
10) J. Joseph, B. Clancy, L. Luo, J. Kinast, A. Turlapov, and J. E. Thomas, "Measurement of sound velocity in a Fermi gas near a Feshbach resonance," Phys. Rev. Lett. **98**, 170401 (2007).
11) B. Clancy, L. Luo, and J. E. Thomas, "Observation of nearly perfect irrotational flow in normal and superfluid strongly interacting Fermi gases," Phys. Rev. Lett. **99**, 140401 (2007).
12) A. Turlapov, J. Kinast, B. Clancy, L. Luo, J. Joseph, and J. E. Thomas, "Is a gas of strongly interacting atomic fermions a nearly perfect fluid?," JLTP **150**, 567 (2008).
13) X. Du, L. Luo, B. Clancy, and J. E. Thomas, "Observation of anomalous spin segregation in a trapped Fermi gas," Phys. Rev. Lett., **101**, 150401 (2008).

7. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

J. E. Thomas
Andrey Turlapov (Post doctoral associate)
Xu Du (Post doctoral associate)
J. Kinast (Graduate Student) Ph. D. May, 2006
B. Clancy (Graduate Student)Ph. D. May, 2008.
L. Luo (Graduate Student) Ph. D. May, 2008.
J. Joseph (Graduate Student)
I. Kaldre (Undergraduate Student) Honors Thesis, BA, May, 2006.
E. Tong (Undergraduate Student)
M. Brown (Undergraduate Student)
D. Weisberg (Undergraduate Student) Honors Thesis.

8. REPORT OF INVENTIONS (BY TITLE ONLY):

None.

## BRIEF OUTLINE OF RESEARCH FINDINGS

### Overview

Optically-trapped, strongly-interacting Fermi gases are models for exotic strongly-interacting systems in nature. For this reason, tabletop experiments with strongly-interacting atomic Fermi gases can provide measurements that are relevant to all strongly-interacting Fermi systems, thus impacting theories in intellectual disciplines outside atomic physics, including materials science and condensed matter physics (superconductivity), nuclear physics (nuclear matter), high-energy physics (effective theories of the strong interactions), astrophysics (compact stellar objects), the physics of quark-gluon plasmas (elliptic flow), and most recently, string-theory (minimum viscosity hydrodynamics).

Recent experiments have been carried out in a three dimensional geometry, where the adiabatic local density approximation is valid. The purpose of this program is to explore strongly-interacting Fermi gases in a two-dimensional pancake geometry, where the simplest approximations break down.

### Findings

In the first period of research in this program, we constructed an entirely new laboratory that is dedicated to experiments using a standing wave $CO_2$ laser trap. This system is now fully operational, and is based on an extremely compact all-optical trapping and evaporative cooling method.

By using a standing wave, we produce a periodic trapping potential with a $5.3\,\mu$ spacing. With 2000 atoms per site, we obtain a quasi-two-dimensional geometry, where the Fermi energy in the weakly confining transverse direction is smaller than the energy level spacing in the tightly confining axial direction. We confine a 50-50 mixture of the two lowest spin states of $^6$Li, and tune a bias magnetic field to a broad Feshbach resonance at 834 G to enable magnetically tunable interactions.

We had two unexpected breakthroughs after the new laboratory became operational. We realized in 2005 that it was possible to measure the energy of the gas at resonance (in the unitary regime) in a model independent manner. To do this, we proved, theoretically and experimentally, that the virial theorem holds. This permits the total energy of the gas to be related simply to the cloud size, despite the fact that the unitary gas is a complicated, non-perturbative many-body system [Phys.

Rev. Lett. **95**, 120402 (2005)]. We realized that the entropy of the gas could be measured by adiabatically sweeping the bias magnetic field to a weakly interacting region, where the cloud size determines the entropy. Using these ideas, we made the first model-independent study of the thermodynamic properties of a unitary Fermi gas, providing energy and entropy data that now is used as a benchmark for the theory groups [Phys. Rev. Lett. **98**, 080402 (2007)]. This data was taken in a single beam trap, to provide reference data for future experiments in the two-dimensional trap.

We also developed a new radio frequency spectrometer in the new laboratory, with the plan of measuring the pairing energy in the quasi-two-dimensional gas. For calibration, we began by measuring the spectrum in a single beam trap in the weakly interacting regime near 528 G, where the scattering amplitude is very small and tunable between positive and negative values. To our surprise, we discovered large amplitude spin-waves [Phys. Rev. Lett., **101**, 150401 (2008)]. The regime of the experiments is far from equilibrium. Our work was highlighted in a Viewpoint Article [Physics **1**, 27 (2008)], which connected it to the condensed matter field of spintronics. Indeed, I have been invited to a conference in Utrecht in January, 2010 that connects cold atoms to the field of spintronics.

Following these initial experiments, we began to characterize the quasi two dimensional gas in the standing-wave trap. We have already obtained initial data on collective modes. We have also measured three-body inelastic loss, which is highly suppressed by the Pauli exclusion principle in two state Fermi gas mixtures. Finally, we have obtained initial radio frequency spectra. We expect the discrete axial quantum states will cause the local density approximation to break down, and the thermodynamic properties, such as the entropy, will exhibit discrete features. The very high atomic density that is attainable in the tightly confined standing wave trap is predicted to produce new bound states. In the near future, we plan to correlate radio frequency measurements of the pairing gap with measurements of the inelastic decay properties. These standing wave experiments are the first to explore a mesoscopic two-dimensional gas, where several thousand atoms are confined in each site. We expect that these studies will be very rich in new results.